ANALYSIS OF A DIRECT ENERGY CONVERSION SYSTEM USING MEDIUM ENERGY HELIUM IONS

A Thesis

by

JESSE JAMES CARTER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Nuclear Engineering

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Approved by:

Chair of Committee, Ron Hart
Committee Members, Leslie Braby
Wayne Saslow
Head of Department, William Burchill

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ABSTRACT

Analysis of a Direct Energy Conversion System Using Medium Energy Helium Ions.

(May 2006)

Jesse James Carter, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Ron Hart

A scaled direct energy conversion device was built to convert kinetic energy of singly ionized helium ions into an electric potential by the process of direct conversion. The experiments in this paper aimed to achieve higher potentials and higher efficiencies than ever before. The predicted maximum potential that could be produced by the 150 kV accelerator at the Texas A&M Ion Beam Lab was 150 kV, which was achieved with 92% collection efficiency. Also, an investigation into factors affecting collection efficiency was made. It was concluded that charge was being lost due to charge exchange occurring near the surface of the target which caused positive target atoms to be ejected from the face and accelerated away. Introducing a wire mesh near the face of the target with an electric potential, positive or negative, which aimed to control secondary ion emissions, did not have an effect on the collection efficiency of the system. Also, it was found that the gas pressure inside the chamber did not have an effect on the collection efficiency. The goal of achieving higher electric potentials and higher efficiencies than previous direct conversion work was met.

DEDICATION

To my parents, who have always supported me.

ACKNOWLEDGEMENTS

First, I would like to acknowledge Dr. Ron Hart for his guidance and diligence in this project, especially when I had no diligence. I also thank my fellow graduate students who aided in my understanding of the accelerator system and charge collection process, especially Avery Bingham and Celestino Abrego. I give a special thanks to Michael Martin who spent countless hours operating the shutter for me. I also thank all of the above for helping to repair and maintain the accelerator system. But most of all, I thank God, without Whom nothing is possible, and with Whom nothing is impossible.

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CHAPTER I

INTRODUCTION

As part of the Department of Energy's Nuclear Energy Research Initiative, Texas A&M University, in collaboration with Sandia National Laboratories and General Atomics Corporation, is developing a Direct Energy Conversion reactor type called the Fission Fragment Magnetic Collimator Reactor (FFMCR). The Department of Energy, through Sandia National Laboratories, is funding experimental verification of the FFMCR concept.

A FFMCR fission fragment collector prototype has been designed at Texas A&M University and is near completion[1)]. The fission fragment collector works by means of Direct Energy Conversion (DEC) - the process of converting the kinetic energy of charged particles released in nuclear reactions to potential energy by decelerating and ultimately collecting the particles on high-voltage plates[2)]. In the Texas A&M University design, singly charged helium ions produced by the Texas A&M K500 Superconducting Cyclotron collide with a collector and may result in electric potentials of 1 MV or greater.

The aim of this thesis is to study the charge collection process that takes place in the FFMCR. Experiments were done on a small-scale collection system that simulates the charge collection process that will take place in the FFMCR. In the FFMCR design, charged fission fragments will have a distribution of charge, speed, and density.

This thesis follows the style of *Nuclear Science and Technology*.

In the small-scale setup, ion charge and speed are kept constant in order to study the collection process alone.

The direct collection process was proposed as early as 1959. Budker suggested that it might "be possible to convert thermonuclear energy directly into high-voltage electrical energy in an industrially economic manner; in this way the steam turbine, the dynamo and the step-up transformer are eliminated"[3)]. An industrial electricity generation process without the need to create steam greatly simplifies the process of generating electricity for a community. While electricity generation by means of steam and turbines is a proven technology, it is not without its shortcomings. The generation of heat from fission fragments in a typical nuclear reactor generally results in thermal efficiencies of only 33 – 35%. The FFMCR is a revolutionary and promising design for its direct conversion to electricity may have much greater efficiency for the conversion of fission energy to electricity.

Previous DEC work has been done by Barr and Moir at Lawrence Livermore National Laboratory as well as by workers at the Texas A&M Ion Beam Laboratory[4-5)]. Both experimental programs used a single-stage plate-type collector to collect ions from a monoenergetic and monodirectional beam produced by an accelerator. In reality, fission fragments have a distribution of energies and directions. These experiments tested factors such as collection efficiency and proper insulation in a more ideal direct conversion environment.

In the experiment by Barr and Moir, voltages as high as 100 kV were produced, but collection efficiency was only 48%[4)]. Previous work in the Texas A&M University Ion Beam Laboratory had a collection efficiency of approximately 90%, but problems with insulation and resistor calibration allowed potentials of only 40 kV[5)]. Research needed to be done to achieve higher voltages and efficiencies by means of improved collection design and proper material selection. It was the aim of the present work to combine previous work in the Ion Beam Lab with new design and materials to produce electric potentials as high as 150 kV with near perfect collection efficiency. Also, an investigation was made into factors affecting collection efficiency in order to determine appropriate conditions necessary for the collection process in the FFMCR.

CHAPTER II

EXPERIMENTAL SYSTEM

1. *Ion Acceleration System*

This section will describe the production and acceleration of necessary ions and the equipment used to do so. The experiment was performed in the Texas A&M Ion Beam Lab using a 150 kV linear accelerator. Refer to Figure 1 during the description of the acceleration system.

The ions used in this experiment are singly charged helium-4 atoms. Helium gas, 99.9% pure, is fed into a Physicon hot cathode ion source. Electrons from a tungsten filament are accelerated toward an anode. Collisions with the helium atoms result in helium ions. The resulting ions are forced into the acceleration column where ions are subjected to an electric potential of up to 150 kV. According to the electric potential equation, $E=qV$, a singly charged atom will accelerate and leave with a kinetic energy of up to 150 keV.

The ions must be transported in a high vacuum environment, $< 10^{-6}$ Torr in this case, to minimize ion-gas collisions and ensure that the ions in the beam all have the same kinetic energy. The term "kinetic" will be omitted and the kinetic energy of the ions in the beam will be further referred to as "beam energy." This is because there are no gravitational potential fields or related potential fields that will alter the ion's kinetic energy until it reaches its final destination in the target chamber. Also, the energy spread of beam ions as they leave the ion source is on the order of 30 eV. This deviation is small compared to the actual ion energy so it will be neglected and the beam is considered monoenergetic.

The beam is introduced into a set of focusing lens electrodes which can generate a beam of millimeter size at the target when properly focused. A way of adjusting the beam current involves focusing and spreading the beam so that the desired current of ions is transmitted through a small collimator near the target. This is the method used in this experiment to obtain desired beam currents.

After leaving the accelerating column, the ions enter a glass cross region. Inside the glass cross are a few instruments for modifying the ion beam. There is a shutter to stop the beam and measure the beam current at this point. This is helpful when first activating the ion beam and also when making adjustments in the target chamber. Also, there is a set of vertical deflection plates. The beam passes through the middle of a set of parallel plates with variable electric field in order to adjust the vertical height of the beam. Typical plate voltages range from 0-200 V. Connected to the bottom of the glass cross is a 6-inch Varian diffusion pump. This pump maintains a pressure of approximately 8E-7 Torr in the glass cross when the beam is not in use and 2E-6 Torr during operation of the beam.

Next, the ion beam heads into a magnetic field generated by the separation magnet. The magnetic field is varied so that only a certain isotope of ions, in this case helium-4, has a trajectory that will lead them to collide with the target. Typical magnetic fields in this region range from 0.01 to 0.1 T depending on the mass and energy of the ion. Since the ion source operates at ~1000 C, there are some background gasses in the

A Physicon Ion Source
B Acceleration Column
C Electron Backstreaming Barrier
D Vertical and Horizontal Deflection Plate Assembly
E Glass Cross Shutter
F Glass Cross
G Diffusion Pump
H Separator Magnet

I First Collimator
J Sweep Plates
K Ion Pump
L Horizontal and Vertical Collimators
M Liquid Nitrogen Cold Trap
N Beam Profile Monitor
O Target Chamber Collimator
P Target Chamber

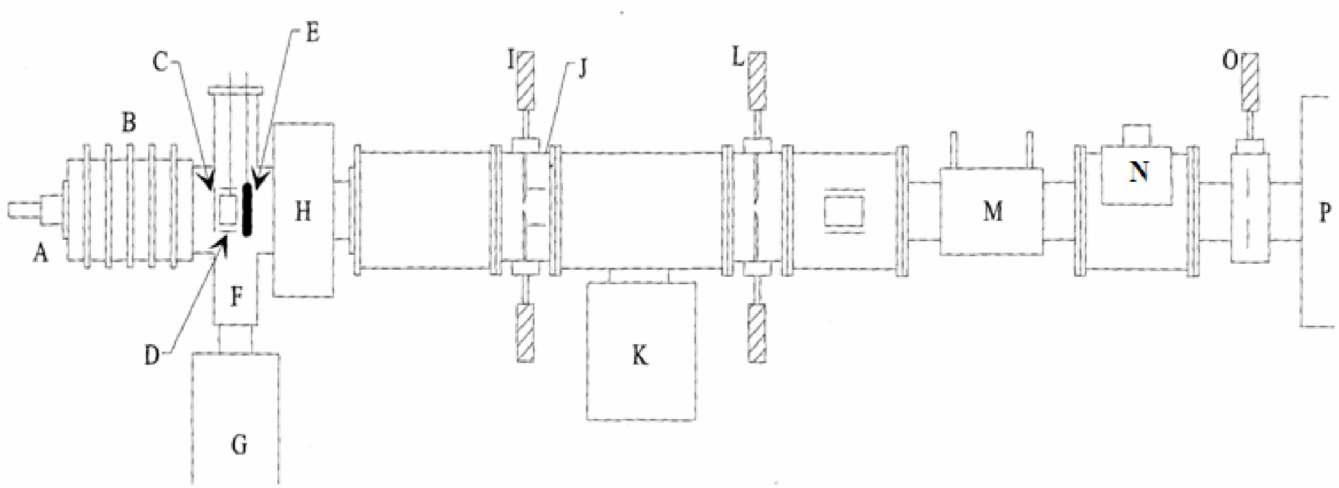

Figure 1 - Accelerator system (Figure courtesy of Kelley Thompson)

ion source and therefore ions of nitrogen, oxygen, water, etc, but the separation magnet ensures that only helium is directed towards the target.

The ion beam now heads down the beam line. The pressure in the beam line is maintained in 10^{-8} Torr range to keep gas collisions to a minimum. There are a few knife-edge collimators in the beam line, but they are not needed in the present work. There is also a liquid nitrogen cold trap near the end of the beam line. This causes substances such as pump oil to condense on the walls of the cold trap to prevent them from entering the target chamber.

Lastly, there is a beam collimator at the end of the beam line just before the target chamber. This is the last instrument to be used in shaping the beam before it enters the target chamber. For this experiment, the beam was collimated to a diameter of 1/8 inch.

2. Target Chamber

The target chamber in this experiment is a large, mostly empty space where ions finally have interactions. Refer to Figure 2 during description of the target chamber. The pressure in the target chamber is on the order of 10^{-8} Torr during operation. The pressure is maintained with a well-baffled diffusion pump as well as a cryopump. As the beam progresses from the source to the target chamber, it may have picked up electrons streaming along with it through collisions with walls, collimators, and other objects. We wish to only have positive ions enter the target chamber, so a small cup is placed in the opening to the target chamber and biased negatively to repel electrons in the beam. The bias cup was kept at a constant -200 V during the experimentation.

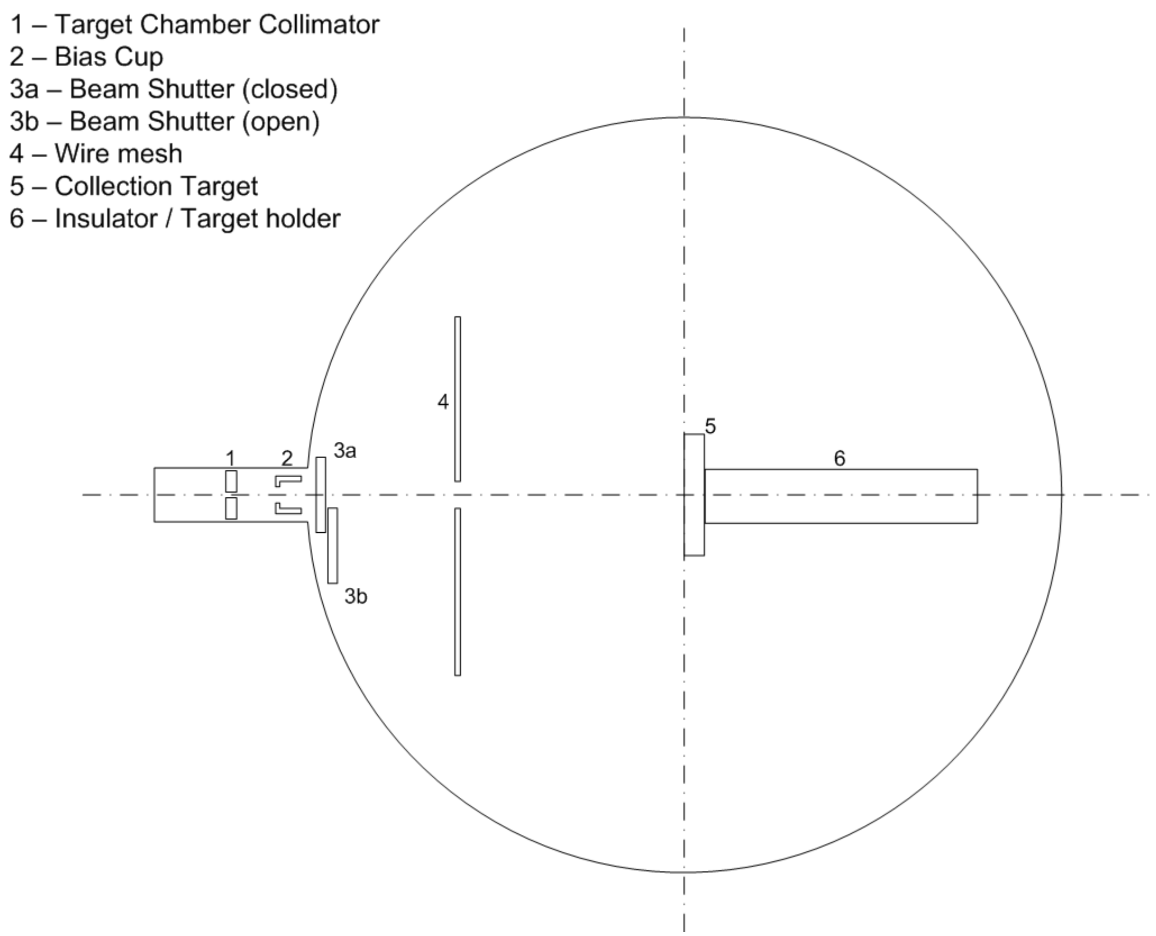

Figure 2 - Target chamber components

Inside the target chamber, there is a shutter attached to an electrometer. Refer to Figure 3 for an electrical schematic of the target chamber. The shutter can be moved in and out of the ion beam from outside the target chamber to allow or disallow the beam from entering the target chamber. If the shutter is "closed," the beam deposits its charge on the shutter and the electrical current is measured. The bias cup discussed above is adjacent to the shutter and repels secondary electrons to give accurate measurements of beam current. We will call the beam current at this point the "shutter current."

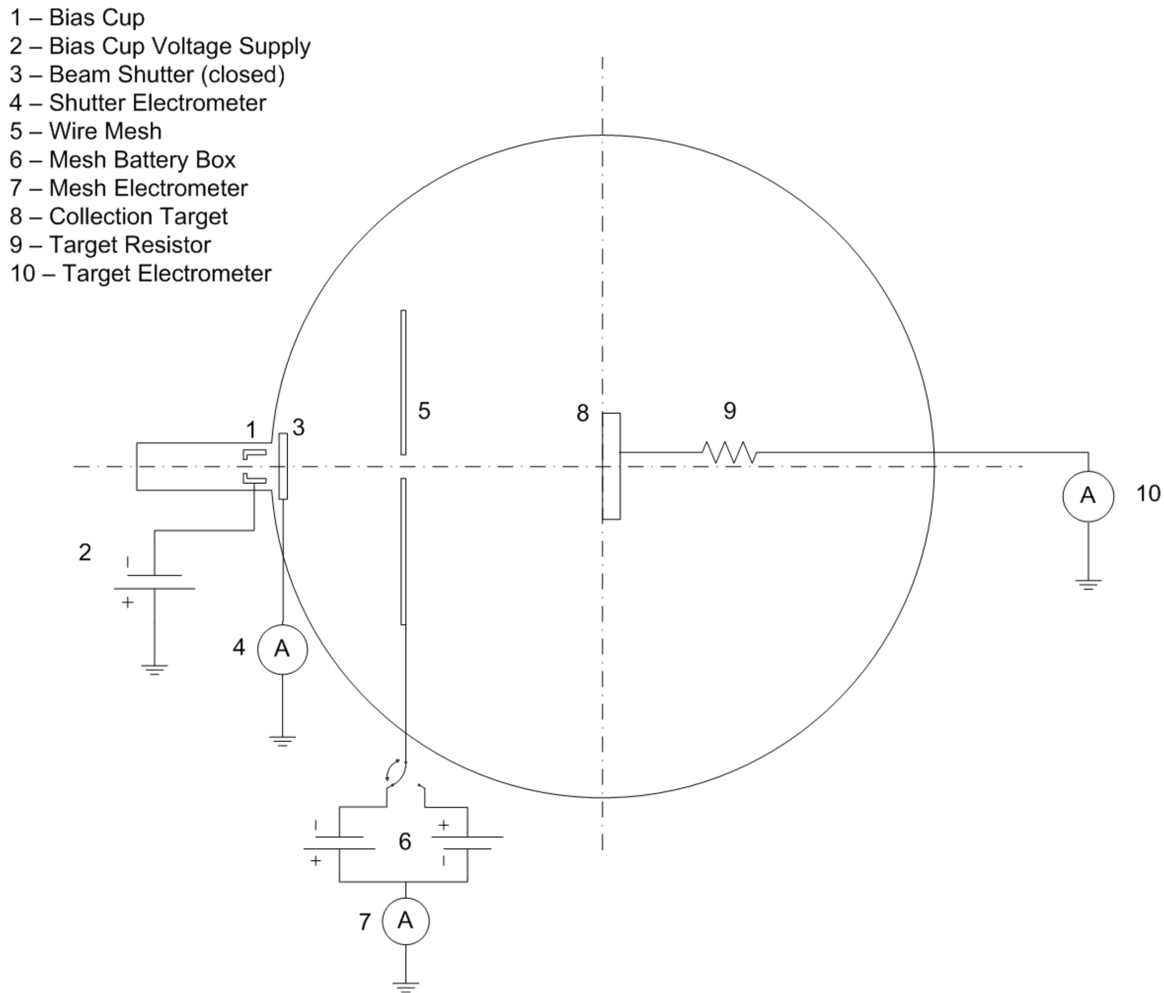

Figure 3 - Target chamber electrical schematic

Also inside the target chamber is a large 70% transmission ion suppression grid. The plane of the grid is perpendicular to the ion beam direction and the beam travels through the center of the grid. There is a hole in the grid to allow the ion beam to travel through it unperturbed. A positive or negative bias can be applied to the mesh to suppress secondary electrons created in the chamber wall near the mesh. This will be used when attempting to determine factors affecting collection efficiency.

A battery box placed outside the target chamber is connected to the mesh inside the chamber. The battery box is a collection of 90 V batteries. The number of batteries connected to the mesh can be varied so the bias of the mesh can be varied from 0 to 540 V in 90 V increments, both positively and negatively. The batteries are inside an insulating case which ensures that charge from ions collected on the mesh can be detected by an electrometer connected to the opposite pole of the battery box.

3. Charge Collection Apparatus

Charge is collected by a cylindrical aluminum disk in the middle of the target chamber. This disk will be referred to as the "target." The target is 2.5 inches in diameter and 0.5 inches thick. Ions are incident on the large face of the target. The target is well insulated from ground by a large piece of Nylatron Blue Nylon, as well as by the high vacuum that exists in the target chamber. The Blue Nylon serves as both an electrical insulator as well as a structural material that extends from the target chamber wall and holds the target in the middle of the chamber. Holes are drilled in the Blue Nylon in which rests the resistors used in the experiment. The spacing of the holes is chosen such that, there will not be a large potential difference between any two points that come in close proximity to each other[6)]. We do not want charge to arc across the vacuum.

The resistors used in this experiment are manufactured by Nichrome Electronics Inc., and each has a verified electrical resistance of 100 GΩ ± 5% up to 90 kV. The electrical circuit of the apparatus is as follows. The target is connected to one resistor or two in series which are connected to another electrometer and then to ground. This gives the charge on the plate a path to ground while passing through an electrical load which simulates electricity usage in a real setting.

CHAPTER III

PROCEDURE

1. Calibration and Material Selection

In previous direct collection work in the Texas A&M Ion Beam Lab, various materials and geometries were used to insolate the charge on the charge collection plate, as well as physically supporting the plate in its proper location. The first step was determining the proper material that worked well as an insulator but was also machinable in order to shape it to hold the target and resistors in place. Also, a type of resistor with very high ohmic resistance was needed. The insulator, insulator shape, and resistors chosen for this experiment were basically chosen through the process of elimination.

Some prior direct collection experiments in the Ion Beam Lab used a goniometer to mount the target apparatus in the middle of the target chamber. Also, polytetrafluoroethylene (Teflon) was used as the insulator and the resistor was made of glass. This system was plagued by charge arcing and non-linear resistor response[5)]. When the specific problem with this system could not be determined, the charge collection apparatus was modified piece by piece until it behaved appropriately.

Once the proper experimental apparatus was selected, constructed, and installed, the electrical resistance was tested with a small 3 kV power supply. It is small in the sense that 3 kV is much less than the voltage we wish to put across the resistor. The resistance of the setup was verified by measuring the current through the resistor at increasing voltages up to 3 kV.

Two electrometers and one current integrator with a current meter were selected and calibrated with a Keithley current source. The current source was previously calibrated to be functional to within a fraction of a percent. Lastly, any leakage current in any of the electrical circuits must be measured and accounted for.

2. Experimentation

The first experiment involved achieving and confirming the maximum target potential allowed by the system. We must use currents generated by the beam for measurements. Charge flow is the only thing we can directly measure with the setup and we can infer what we need from that. The target potential verification is done by increasing the target current to what we will call a “threshold current.” The experiments start with low beam currents, < 100 nA, and observing the target current. The shutter current is verified to be a specified value. The shutter is moved out of the beam and the target current will match or approach the shutter current. Any discrepancy between shutter and target currents will be discussed later. When the target current is recorded, the shutter is closed and the beam current is recorded that corresponds to the target current. Then the shutter current is increased and the process is repeated until the target current does not increase any further, meaning a threshold current is found.

The shutter current must be measured again after the target current because the ion source does not output a constant current. When the shutter is closed, approximately one second passes before the electrometer reads the entire beam current. This introduces a source of error because the beam current could change in that small amount of time. A close investigation of the beam shows that the beam current does not change by more than 2% over the course of a second.

Since there is an electrical resistance in the path of the charge, Ohm's Law gives the electric potential on the target. When the positive beam ions encounter the electrical field due to charge on the plate, they will are repelled and begin to slow down as given by E=qV, where E is the loss (or gain according to particle charge and direction) of energy, q is ion charge, and V is voltage. For example, if one 100 GΩ resistor has 50 nA through it, the potential on the target is 5 kV. If the beam energy prior to entering the target chamber is 50 keV, the beam will reach the target at 50-5=45 keV. When the beam current becomes high enough, target current, and therefore electric potential, will be sufficiently high to completely slow beam ions. This current is called the threshold current – the highest target current achievable. In the example where the beam energy is 50 keV and the resistance is 100 GΩ, the threshold current should be 500 nA because the maximum target potential should be 50 kV.

Provided that the beam energy is well-known, the presence of a threshold current, or "threshold situation," verifies the theory that a given beam energy and given resistance can create a maximum electric potential equal to V=E/q. Now we can say that the voltage and current are well known and the resistance of the system can be measured by Ohms Law. We can also verify that the resistance is constant through a large range of voltages. This helps to determine the resistances of several resistors which will be used in the large scale direct collection test at the Texas A&M Cyclotron.

The next experiment was to test the collection efficiency of the system. It is possible that all charge incident on the shutter may not emerge from the back end of the collection apparatus and flow through the electrometer. We investigated this by looking at collection efficiencies. The collection efficiency of the system is defined as the ratio of the target current to shutter current. The collection efficiency was plotted at different beam energies to see if the energy of the ions had an effect.

Also, if the collection efficiency is less than unity, then either positive charge is lost from the target or electrons are accelerated to the target. For this reason we placed a 70 % transmission nickel wire mesh in front of the target to capture reflected ions that strike it. If positive ions are not depositing their charge in the target, or if positive ions are being ejected from the target, the collection efficiency will drop. A hole was cut in the middle of the mesh to allow the beam to pass through it, so the transmission will be greater than 70 %. Regardless, the mesh should still capture ions inside the target chamber.

The positive ions that strike the target chamber wall or mesh will produce secondary electrons[7)]. Secondary electrons will be attracted to the target because of their opposite charge. This is very undesirable since the negative electron will cancel a positive charge that had already successfully deposited its charge in the target. For this reason, a voltage bias was placed on the mesh and the collection efficiency of the system as well as the current on the mesh were measured to see if the bias had any effect.

A negative potential on the mesh should help reduce losses due to secondary electron emission from the target chamber wall. The negative electric potential should repel these electrons and keep them in the wall of the target chamber. Also if positive ions escape the target, some may strike the mesh. If a positive potential is placed on the mesh. Any secondary electrons produced in the walls or mesh should be attracted to the mesh. This is desirable so that the electrons do not reach the target and cause charge cancellation.

An investigation was made into the vacuum conditions necessary for high collection efficiencies. If the gas atoms in the target chamber interact with the ion beam, there may be electron ejection from the atom.[6)] These electrons will be attracted to the positively charged target and cancel some charge. The gas pressure inside the chamber was increased to see if the collection efficiency was affected. Another way to look at this phenomenon is through a reaction rate approach. The reaction rate density of beam ions with gas atoms is $RRD=N*\sigma*\varphi$, where N is the number density of atoms in the gas, σ is the effective cross sectional area of the gas atoms and φ is the flux of the ion beam. The flux is equal to the current if each ion has a charge of 1 e. If the beam current is increased, there will be more reactions with the gas. Also, if the gas pressure is increased, the density of gas atoms in the target chamber will increase and cause more reactions with the beam. Therefore, increasing the gas pressure should have a negative impact on collection efficiencies, if indeed the reaction rate in the gas is substantial.

Since we have a way of measuring current at the shutter and target, we must assume that any loss of charge happens between these two points. Several possibilities of charge interaction have been identified and the above experiments should give an indication as to the factors affecting collection efficiency.

CHAPTER IV

RESULTS AND DISCUSSION

This section will present figures representing experimental data followed by a discussion of that data.

Table 1 - Threshold currents and corresponding target potentials, 100 ± 5.00 GΩ resistance

Beam energy	Maximum target current	Target potential
20 keV	204 ± 5.84 nA	20.4 ± 1.18 kV
50 keV	506 ± 13.6 nA	50.6 ± 2.87 kV
80 keV	802 ± 22.0 nA	80.2 ± 4.57 kV

Table 2 - Threshold currents and corresponding target potentials, 200 ± 7.07 GΩ resistance

Beam energy	Maximum target current	Target potential
20 keV	101 ± 2.08 nA	20.2 ± 0.81 kV
40 keV	202 ± 4.16 nA	40.4 ± 1.63 kV
60 keV	303 ± 6.8 nA	60.6 ± 2.50 kV
80 keV	398 ± 9.2 nA	79.6 ± 3.31 kV
100 keV	498 ± 12.4 nA	99.6 ± 4.25 kV
120 keV	602 ± 12.9 nA	120 ± 4.90 kV
140 keV	705 ± 15.7 nA	141 ± 5.81 kV
150 keV	743 ± 16.4 nA	**149 ± 6.10 kV**

Results of the threshold current experiments very closely mirrored predictions. The maximum potential achieved was 149 ± 6.10 kV. In every instance, the target current reached its maximum value precisely as expected. Table 1 and Table 2 show maximum target currents for varying beam energies and target resistances. The threshold current described earlier is the maximum target current in each case. Figure 4 - Figure 7 that follow are selected graphical demonstrations of the current maximization or threshold current. The dominant source of error is due to fluctuations in beam current.

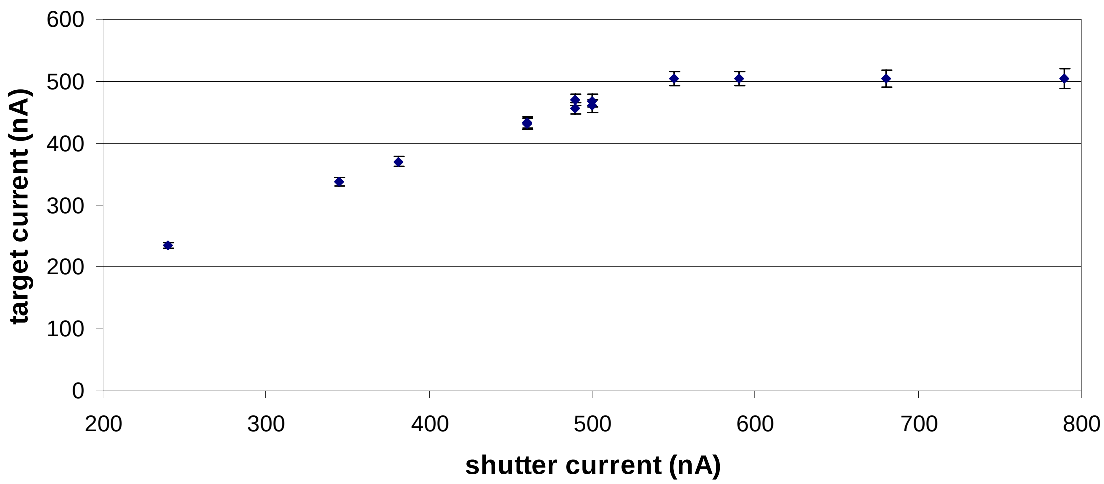

Figure 4 - 50 keV beam, 100 GΩ resistance

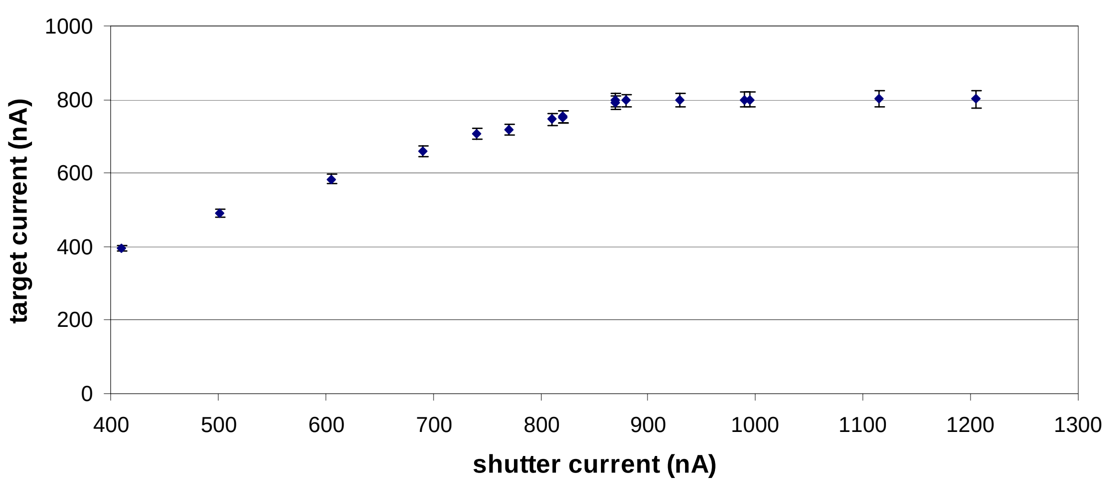

Figure 5 - 80 keV beam, 100 GΩ resistance

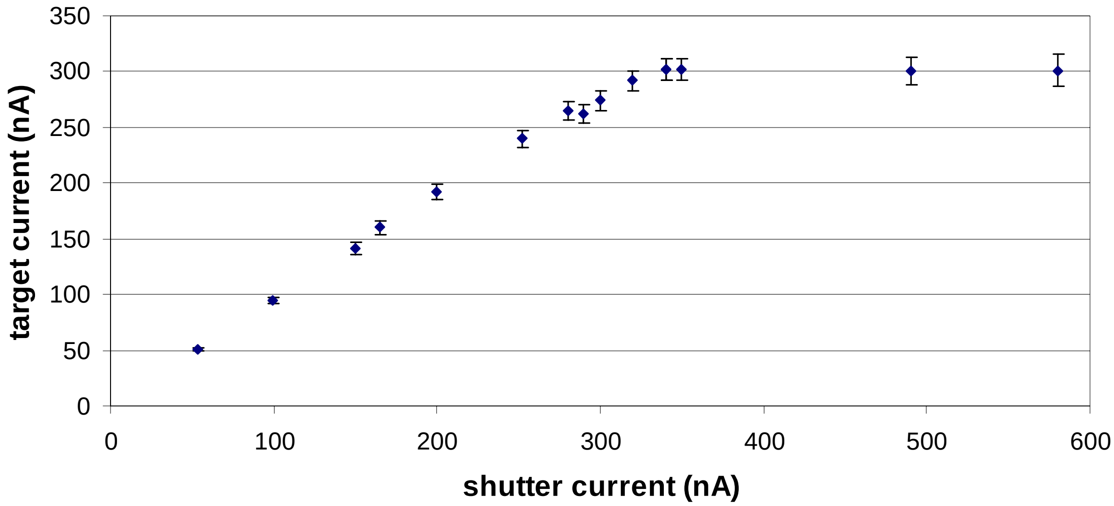

Figure 6 - 60 keV beam, 200 GΩ resistance

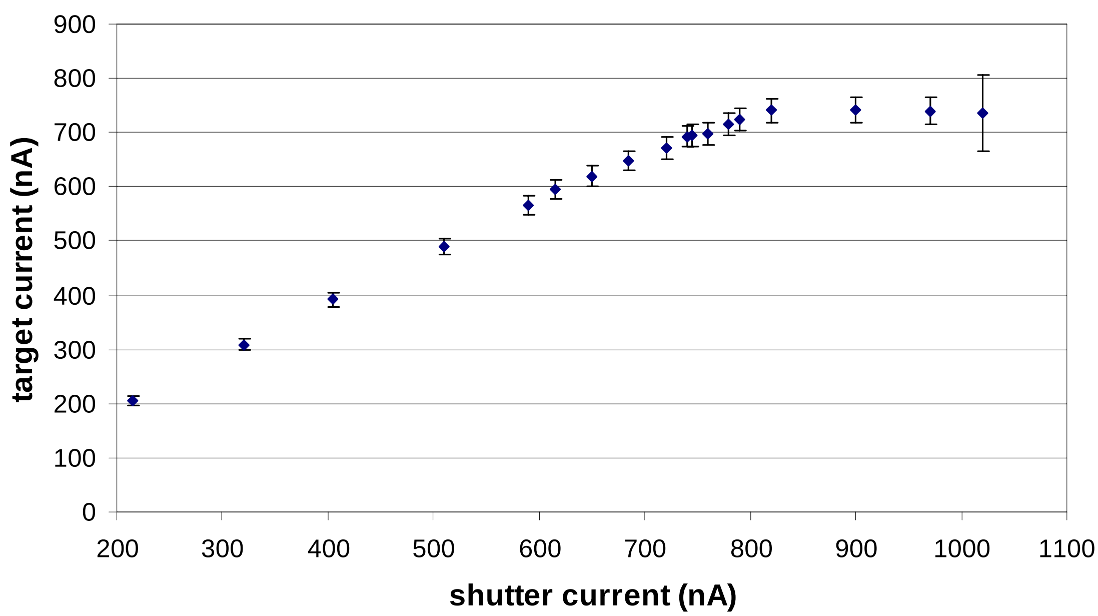

Figure 7 - 150 keV beam, 200 GΩ resistance

The theory section predicted a threshold current and the above data shows sufficient evidence to prove such currents. In the experiments, the beam current was increased far enough beyond the threshold limit to show that such a threshold exists. One can assume that further increasing beam currents beyond those used in the experiment will yield the same result, provided that the experimental setup can sufficiently control any effects from such large amounts of charge. Furthermore, through the use of Ohm's law, the existence of threshold currents proves the existence of an electric potential on the target that is proportional to the ion beam energy. 800 nA and 100 GΩ resistance yielded 80 KV of electric potential and 743 nA and 200 GΩ resistance yielded 149 KV of electric potential. This is 50% higher than the potential produced in the experiments by Barr and Moir[4)]. The efficiency of this experiment is also much higher than the Barr and Moir experiments. Collection efficiency will now be discussed.

The collection process in the experiment is not entirely perfect. Observe in Figure 4 - Figure 7 that in all cases the target current is less than the beam current meaning that the collection efficiency less than unity. Collection efficiency, defined as the ratio of target current to beam current, is shown versus increasing beam current in Figure 8 and Figure 9. In all cases, the collection process is > 89% efficient up to the threshold current. Collection efficiency drops with increasing beam current when the threshold is reached. This is expected because ions begin to be turned back from the target after threshold current is reached and do not impart their charge to the target. In this excessive charge flow situation, the excess ions are no longer being "collected" and the term "collection efficiency" no longer applies. Collection efficiency should indeed be defined as the ratio of target current to beam current as long as a threshold situation is not present.

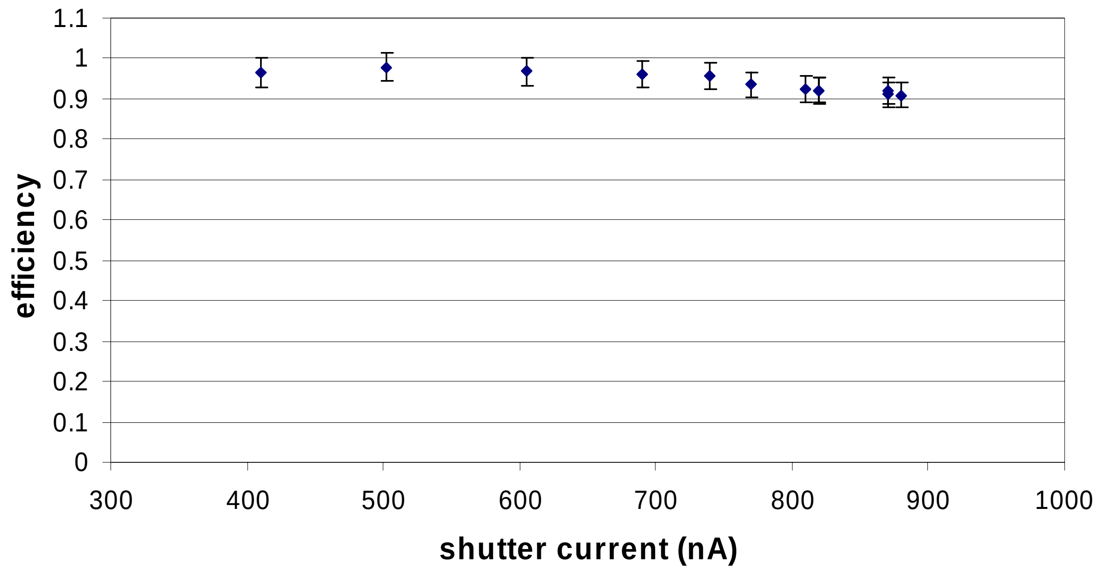

Figure 8 - Collection efficiency, 80 keV beam, 100 GΩ resistance

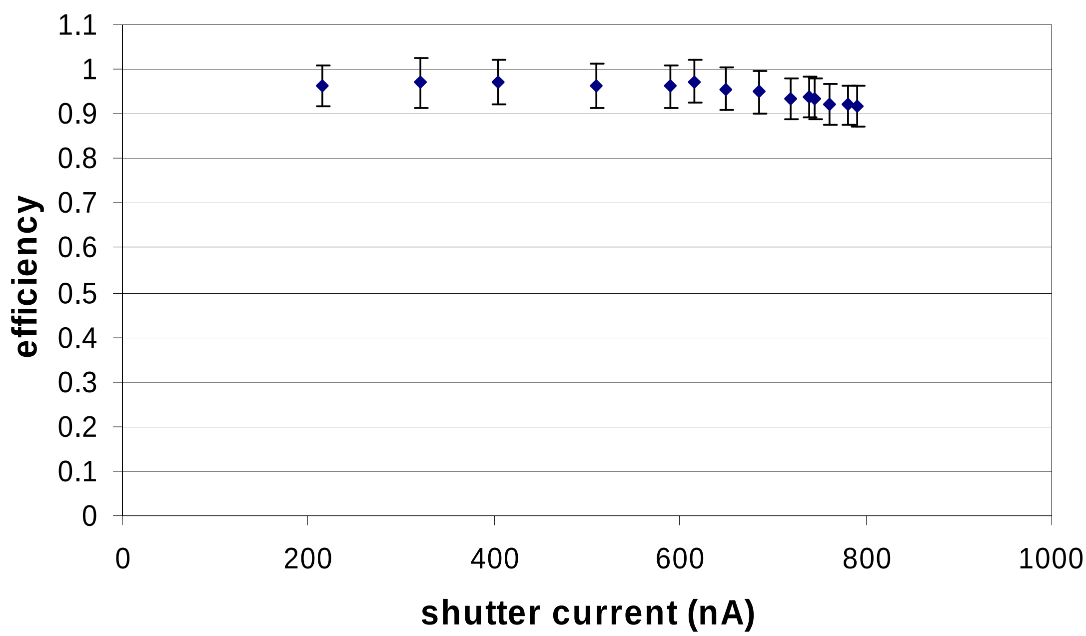

Figure 9 - Collection efficiency, 150 keV beam, 200 GΩ resistance

Note that in the collection efficiency curves, the collection efficiency is not constant. Collection efficiency slowly decreases as beam current increases. Through all beam energies, efficiencies ranged from 89 - 99%. Table 3 and Table 4 show a summary of collection efficiencies for all beam energies used.

Table 3 - Collection efficiencies, 100 GΩ resistance

beam energy	minimum efficiency	maximum efficiency
20 keV	0.934 ± 0.039	0.964 ± 0.037
50 keV	0.923 ± 0.034	0.983 ± 0.045
80 keV	0.920 ± 0.031	0.979 ± 0.036

Table 4 - Collection efficiencies, 200 GΩ resistance

beam energy	minimum efficiency	maximum efficiency
20 keV	0.949 ± 0.033	0.978 ± 0.036
40 keV	0.937 ± 0.038	0.982 ± 0.034
60 keV	0.907 ± 0.032	0.982 ± 0.04
80 keV	0.892 ± 0.034	0.976 ± 0.04
100 keV	0.905 ± 0.033	0.992 ± 0.057
120 keV	0.909 ± 0.032	0.987 ± 0.041
140 keV	0.912 ± 0.031	0.980 ± 0.041
150 keV	0.921 ± 0.044	0.972 ± 0.051

In order to understand why collection efficiency is less than unity, it is helpful to examine the physical processes that occur as an ion enters the target. According to Knoll[7)], a heavy charged ion slows down in matter by interaction with the orbital electrons in the absorber, which in this case is the target. Electrons become excited or completely removed from the target atoms. The electrons that are completely removed from the atom have a tendency to recombine with the atom from which it was removed. But when the velocity of the ion becomes sufficiently low, the ion begins to pick up electrons from the target and becomes neutral. The resulting target atom is nearly at rest but now is missing an electron. If this ion is on or near the surface of the target, and there is a large amount of positive charge deposited inside the target, the ionized target atom will be repelled and can be ejected from the target.

As the beam current increases, the potential of the target increases and beam ions collide with the target at slower velocities. Slower ions will be closer to the surface when they become slow enough to have charge exchange with the target atoms. So as beam current increases, a larger fraction of beam ions will have interactions near the surface that cause positive ions to be ejected from the surface, resulting in an increasing loss of charge. This is one possible explanation for the downward slope of the collection efficiency curves.

In order to observe positive ions escaping the target, the current on the wire mesh was observed. Figure 10 shows that there is indeed some charged particles collected and/or secondary electrons emitted by the mesh in sub-threshold conditions.

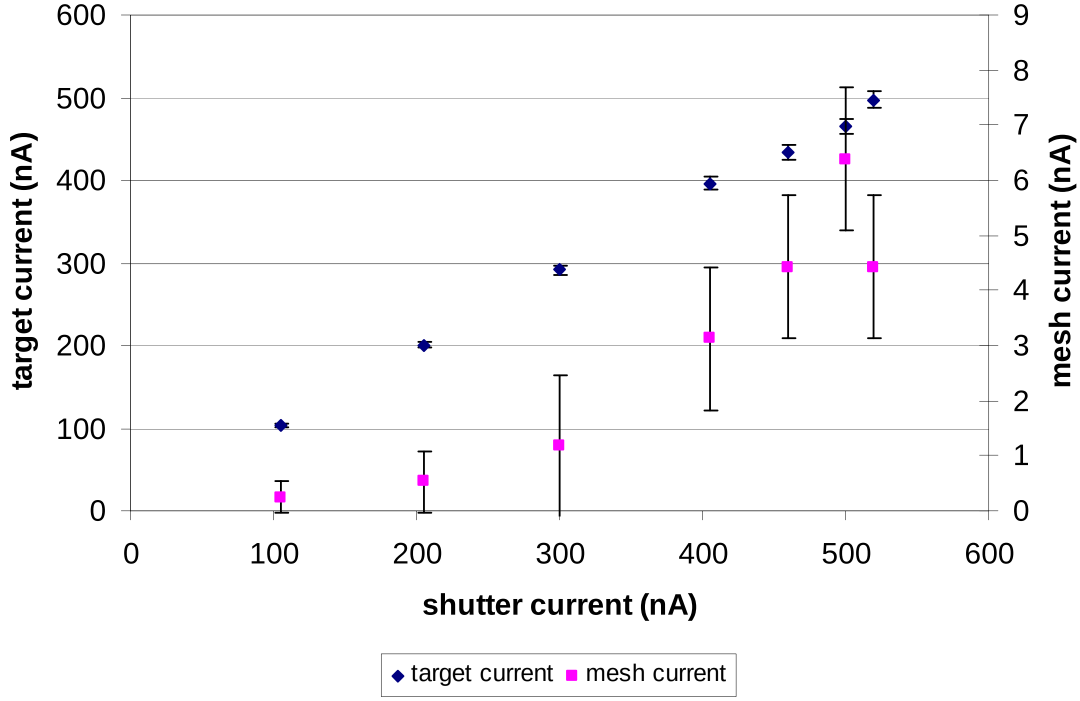

Figure 10 - Target and mesh currents, grounded mesh, 100 keV beam, 200 GΩ resistance

The next investigation consisted of applying a constant electric potential to the mesh and observing any change in the collection efficiency. Beam energy was 100 keV and the mesh was biased both positively and negatively. The results are shown in Figure 11 through Figure 14. The figures have rather large error bars due to large oscillations in mesh current during recording

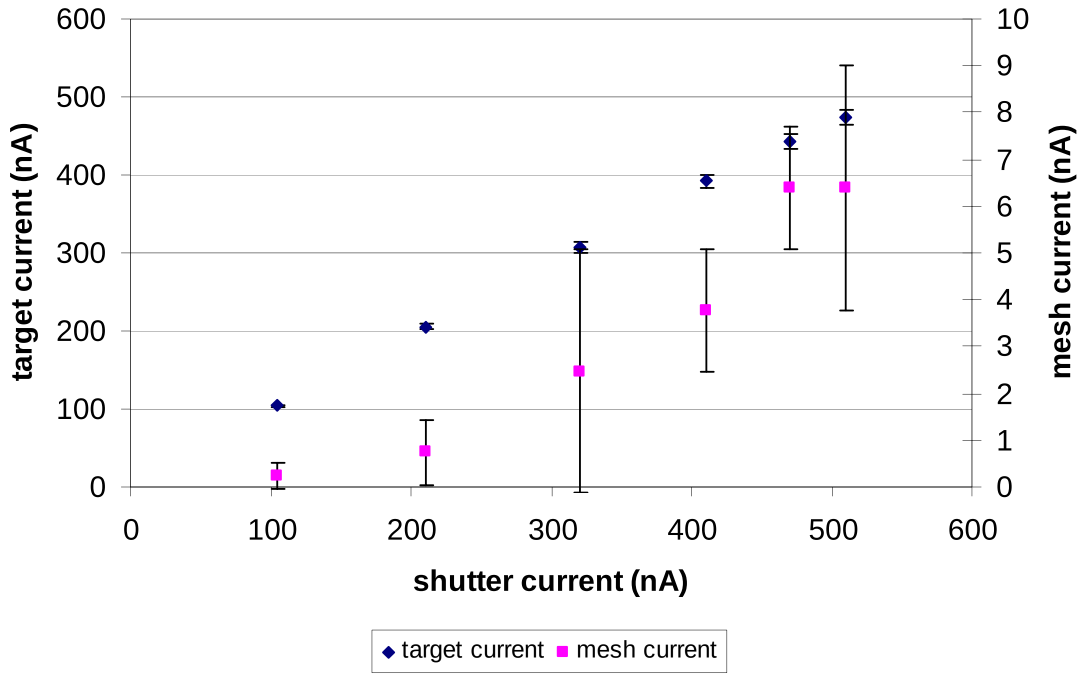

Figure 11 - Target and mesh currents, mesh bias +180 V, 100 keV beam, 200 GΩ resistance

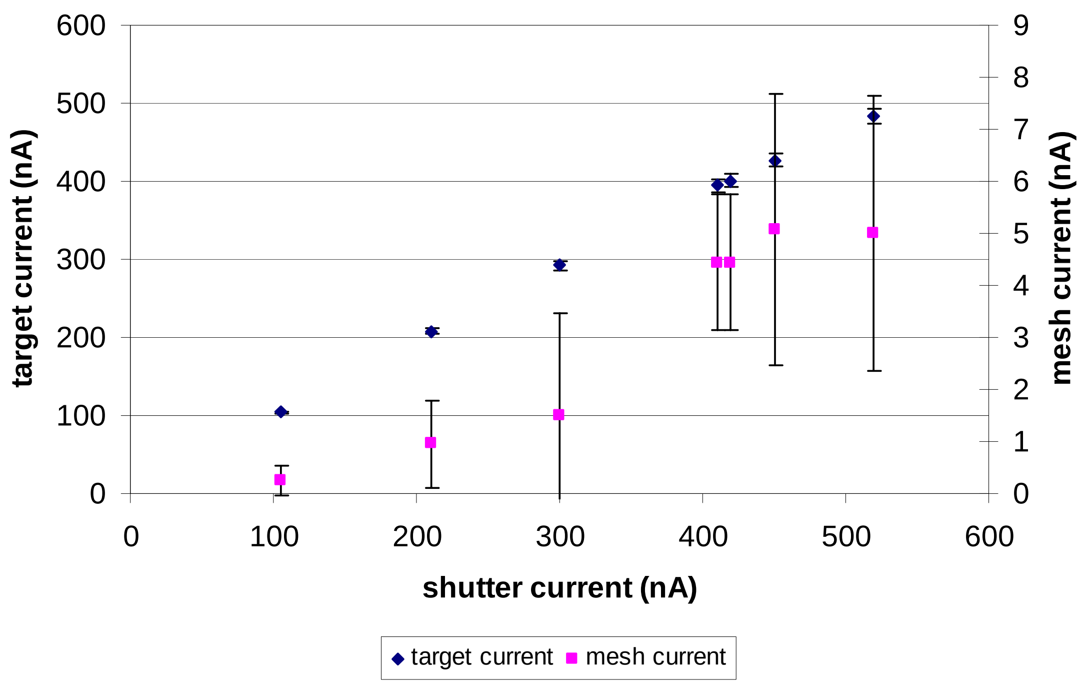

Figure 12 - Target and mesh currents, mesh bias +540 V, 100 keV beam, 200 GΩ resistance

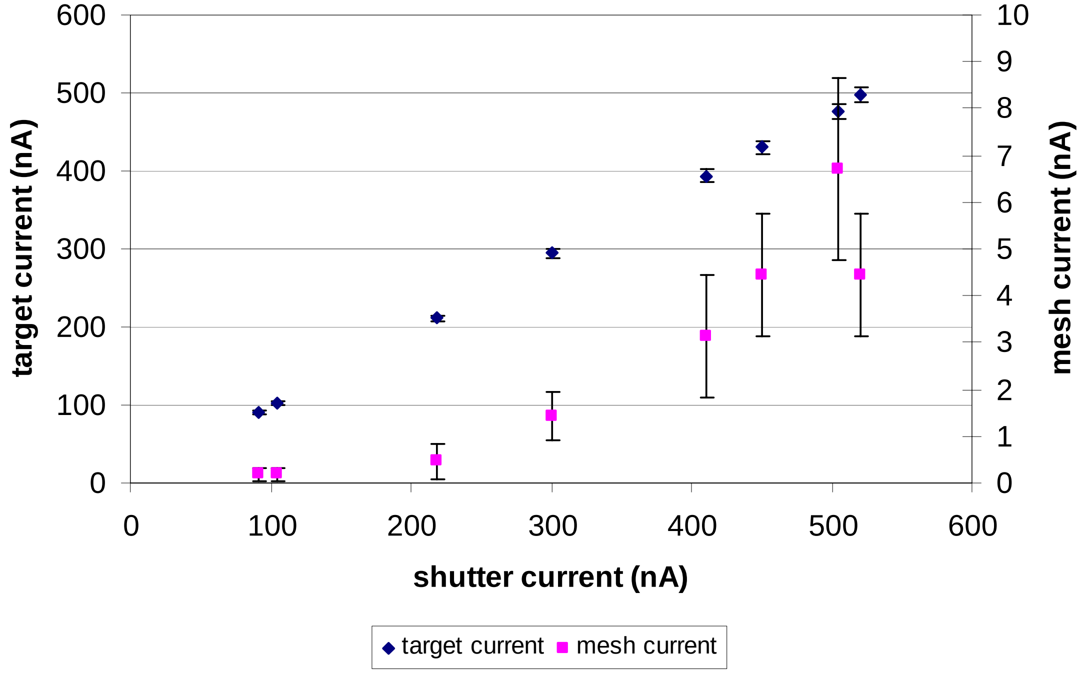

Figure 13 - Target and mesh currents, mesh bias -180 V, 100 keV beam, 200 GΩ resistance

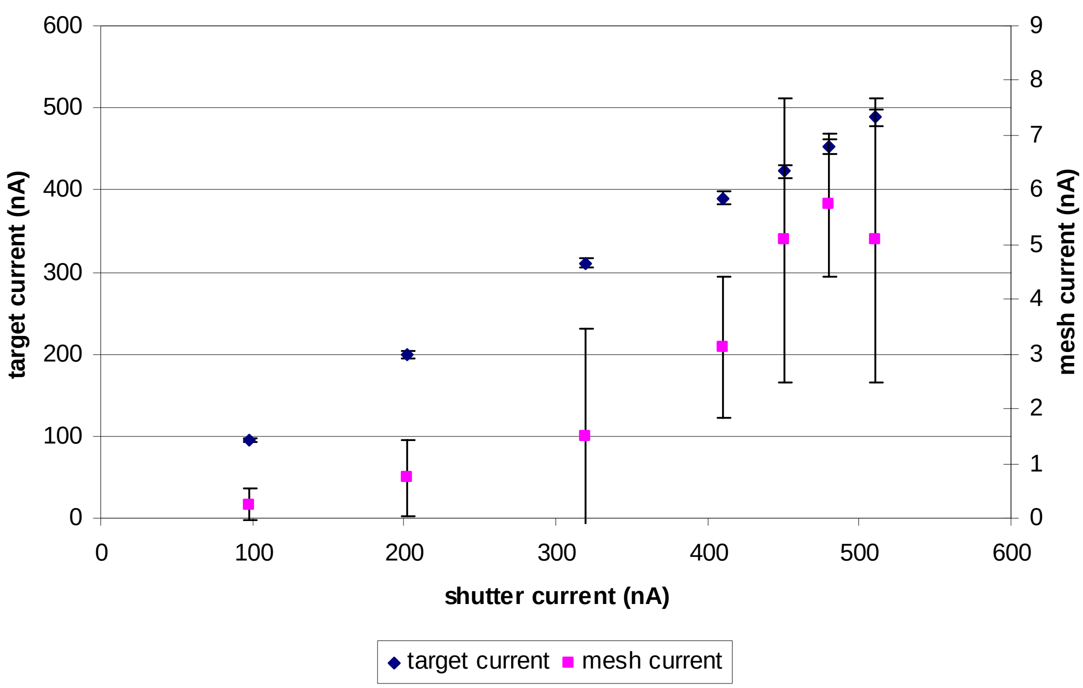

Figure 14 - Target and mesh currents, mesh bias -360 V, 100 keV beam, 200 GΩ resistance

There is no clear indication that the applied electric potentials sufficiently suppressed secondary ion interactions. It is possible that higher potentials are necessary to create the necessary effect.

If a poor vacuum condition were to blame for non-ideal collection efficiency, an attempt to quantify this effect was made. Collection efficiency was measured as the pressure was increased. The pressure range spans almost two orders of magnitude. If poor vacuum conditions were responsible for the non-ideal efficiency, increasing the pressure almost 100-fold should magnify this effect. Figure 15 shows the results from that test.

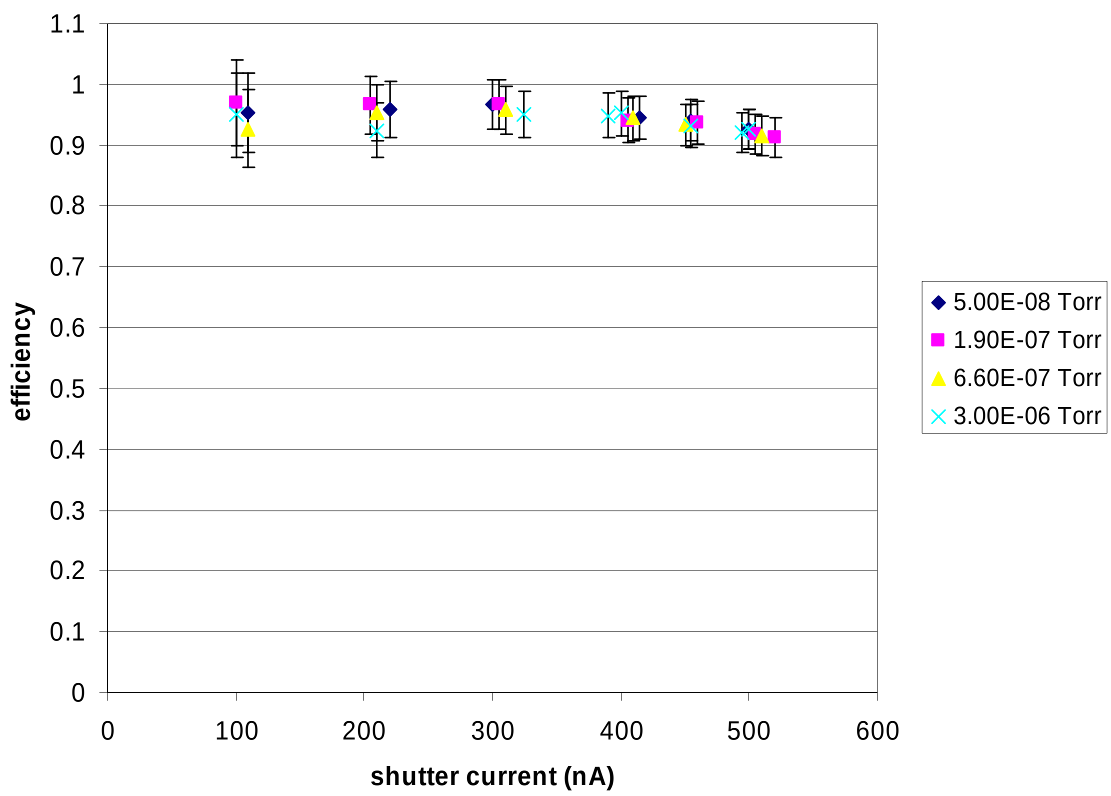

Figure 15 - Collection efficiency and target chamber pressure, 100 keV beam, 200 GΩ resistance

The efficiency curves for all pressure levels have the same shapes and magnitudes. It appears that the change in vacuum level was not causing a change in the collection efficiency curve. If a process inside the target chamber were to be blamed for the loss of collection efficiency, interactions with the gas atoms cannot be considered.

Though there may be other explanations for the positive current on the mesh when there should be none. One reason could be due to collisions of beam ions with the collimator. Ions may have collisions with the collimator edge and deflect slightly away from the beam, striking the mesh.

CHAPTER V

CONCLUSION

This thesis helps to further the work in the field of direct collection. In the Ion Beam Lab at Texas A&M University, higher electric potentials have been achieved than other experiments in this area. 150 kV of electric potential was generated on the collection plate with very high collection efficiency. The materials and design used in this experiment, as well as the study on the factors affecting collection efficiency, will help aid in the design of a more powerful direct collection experiment at the Texas A&M Cyclotron and beyond.

There is still room for future work in this area. Currently, the collection efficiency is not perfect, and work can be done to suppress positive ions emerging from the face of the target and return them to the target. Perhaps a different target material can be used, or maybe a different projectile. Not all factors affecting collection efficiency have been studied. However, the results contained in this paper agree very closely with theory.

REFERENCES

1) D. B. King, G. E. Rochau, D. S. Oscar, C. W. Morrow, P. V. Tsvetkov, R. R. Hart, R. Gallix, "Experimental Verification of Magnetic Insulation in Direct Energy Conversion Fission Electric Cells", *Transactions of the American Nuclear Society*, **91**, 2(2004).

2) G. H. Miley, *Fusion Energy Conversion,* American Nuclear Society, Hinsdale, IL, 77 (1976).

3) G. I. Budker, "Thermonuclear Reactions in a System with Magnetic Stoppers and the Problem of Direct Transformation of Thermonuclear Energy into Electrical Energy," *Plasma Physics and the Problems of Controlled Thermonuclear Reactions,* Vol. III, Pergamon Press, London, England, 25 (1959).

4) W. L. Barr, R. W. Moir, "Test Results On Plasma Direct Converters," *Nuclear Technology/Fusion*, **3**, 98(1983).

5) A. Bingham, *Investigation Into Direct Energy Conversion With Medium Energy Helium-Ion Beams*. M.S. Thesis, Texas A&M University, 19 (2004).

6) R. Latham, *High Voltage Vacuum Insulation Basic Concepts and Technological Practice*, Academic, San Diego, CA, 20 (1995).

7) G. F. Knoll, *Radiation Detection and Measurement*, 3rd Ed., John Wiley & Sons, Inc., New York, 30 (2000).

VITA

Jesse James Carter was born on October 9, 1980 in Irving, Texas. He started college in 1999 at Texas A&M University. He received his B.S. in Nuclear Engineering in Fall 2003 and M.S. in Nuclear Engineering in May 2006. He is enrolled in the Ph.D. program at Texas A&M University. He can be reached at 2512 Cantrell, Irving, TX 75062. His email address is jesse.carter@gmail.com.